Improving Sensor Network Convergecast Performance with Directional Antennas

Javier Schandy
Universidad de la República
jschandy@fing.edu.uy

Simon Olofsson
Imperial College London
simon.olofsson15@imperial.ac.uk

Leonardo Steinfeld
Universidad de la República
leo@fing.edu.uy

Thiemo Voigt
Uppsala University
RISE SICS
thiemo@sics.se

Abstract

The use of directional antennas for wireless communications brings several benefits like increased communication range and reduced interference. One example of directional antennas are electronically-switched directional (ESD) antennas that can easily be integrated into Wireless Sensor Networks (WSNs) due to their small size and low cost. However, current literature questions the benefits of using ESD antennas in WSN due to the increased likelihood of hidden terminals and increased power consumption. This is mainly because earlier studies have used directionality for transmissions but not for reception.

In this paper we introduce novel full stack optimizations in order to fully utilize the benefits of using directional antennas. We modify the MAC, routing and neighbor discovery mechanisms to support directional communication. We focus on convergecast investigating a large number of different network topologies. Our simulation results show that in networks with dense traffic, directional antennas achieve up to 24% higher packet delivery rates, a 55% decrease in energy consumption, and a 46% decrease in the energy per received packet.

Categories and Subject Descriptors

C.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Design, Performance

Keywords

Wireless sensor networks, Wireless communication, Protocols, Directive Antennas, Convergecast

1 Introduction

Over the past few years there has been an increase in Wireless Sensor Network (WSN) deployments, such as in smart agriculture and factory automation [1, 14]. These applications require networks with increasing density and application throughput. WSN nodes are designed to be of small size and battery powered to enable large and distributed applications. They are composed of a microcontroller, sensors and a radio transceiver, the latter being the most power consuming component.

The use of directional antennas such as electronically-switched directional (ESD) antennas in WSN increases the communication range and can reduce interference with neighbor nodes by directing the transmitted power in a given direction [28]. An example of an ESD antenna is the SPIDA, designed by Nilsson [20]. The SPIDA antenna is a low cost ESD antenna with six RF switches that allow nodes to change antenna direction by setting GPIO pins. The antenna gain is about 6dB in the main direction, and has a half power beamwidth of 127° [24].

While there is consensus that ESD antennas in WSN can provide several benefits for specific applications like high throughput bulk forwarding [27] or radio tomographic imaging [30], the benefits of using them for convergecast applications has been questioned with diverse results. While some research shows that ESD antennas can reduce channel contention and the radio duty cycle [28, 19], other research shows that they provide limited benefits that can be only achieved under specific conditions [26].

In this paper we target convergecast applications on top of UDP/IPv6/RPL/6LoWPAN/IEEE 802.15.4 protocols, as they are some of the most common in WSNs. Convergecast is a typical data collection application where every node sends packets periodically to the sink node.

Our novel approach is to jointly optimize the neighbor discovery, medium access and routing protocols to support directional communication. The antenna pair selection is optimized (in terms of energy efficiency) by minimizing the number of antenna directions in use by the nodes, as this prevents unnecessary transmissions and listening in directions without neighboring nodes. But from a communication perspective, the antenna pairs with better received sig-

International Conference on Embedded Wireless
Systems and Networks (EWSN) 2019
25–27 February, Beijing, China

ISBN: 978-0-9949886-3-8

nal strength (RSS) should be used to improve the link quality. We compare both techniques by analyzing their impact on the average Radio Duty-Cycle (RDC) and Packet Delivery Rate (PDR) of the network. Finally, we combine these ideas with routing protocol optimization by minimizing the number of links that each node establishes, and modify Contiki's RPL implementation to use this information. RPL is a proactive routing protocol based on a tree-oriented strategy where each node has a prefered parent as next hop for sending messages to the sink. To evaluate these protocols, we extend the COOJA network simulator to enable the use of directional antennas in a new radio medium, where the directional radiation pattern is modeled as a function of the angle between the transmitter and the receiver node. Transmission success is determined by the signal strength of the received packets, which introduces capture effects [18]. The capture effect is a phenomenon whereby a node can demodulate a signal with higher RSS despite interference from a weaker signal on the same channel, provided some conditions are met [17]. We analyze the different protocols through over 400 simulations with different network topologies and transmission rates, achieving up to 24% increase in PDR and 55% decrease in RDC.

The main contributions of this work are: (i) DirMAC, the first MAC protocol for ESD antennas in WSNs, (ii) a novel technique to optimize antenna pair selection between nodes, including the proposal of a routing protocol optimization method that minimizes the number of links that each node establishes, (iii) results showing that these protocols can significantly increase the PDR and decrease the RDC compared to networks using omnidirectional antennas.

The paper is organized as follows: Section 2 introduces related work in the use of ESD antennas in WSN. In Section 3 we present the design of our protocols. In Section 4 we introduce the modifications made to the COOJA simulator to support ESD antennas, and in Section 5 we evaluate our protocols on different network topologies and densities for convergecast. Finally, in Section 7 we conclude our work.

2 Related Work

The most recent work regarding the use of ESD antennas in WSN is presented by Tarter et al. [26]. They make a quantitative analysis of the performance of WSN protocols in a convergecast application using directional transmissions and omnidirectional receptions, and conclude that directional antennas provide limited benefits that can only be leveraged under specific conditions. They also state that when using ESD antennas there is an increased likelihood of hidden terminals. However, in this work nodes have different ranges for transmission and reception as the latter is done omnidirectionally, and thus doing CSMA-CA (the de-facto MAC protocol in WSN) is inappropriate as the hidden terminal problem is exacerbated when the channel is checked in a shorter range than the transmission range. Also, a fair analysis of the power consumption cannot be performed as they do not use any RDC mechanism in the MAC layer. Finally, they simulate the WSN with the Castalia simulator [3] which does not model the hardware layers (i.e. radio hardware ACK) and the capture effect, which is key to reducing the interference.

Mottola et al. [19] also study the impact of introducing ESD antennas in WSN. They show that they can increase the performance of WSN by reducing the radio on time per delivered packet and increasing the packet delivery rate. But they also observe that, with increased network densities, parents found beyond the omnidirectional range are more likely to be affected by collisions. This is a consequence of using directionality only for packet forwarding, and relying on omnidirectional communications for packet reception, MAC and routing protocols.

Varshney et al. [28] show that using directional transmissions and receptions together considerably reduces channel contention by exploiting the capture effect and allowing simultaneous communication flows between multiple nodes. They do not target convergecast but predefined point-to-point transmission scenarios.

Several works have studied how to implement neighbor discovery mechanisms in networks with nodes that use ESD antennas [23, 29, 10, 11]. These mechanisms are straight forward in networks with omnidirectional antennas because a single broadcast message can be received by every possible neighbor, but they present some challenges when we introduce directional antennas as we may reach different neighbor nodes for every antenna combination. An example of a Neighbor Discovery mechanism for ESD antennas is the SAND protocol proposed by Felemban et al. [10]. SAND is a serialized mechanism that allows all the nodes in the network to find their neighbors and the best antenna pair between them. In Section 3.1, we describe the design of a version of this protocol with minor modifications to collect the link metrics, registering all the possible antenna combinations for latter optimization.

The use of ESD antennas in WSN is also studied for other applications different from convergecast. Wei et al. [30] show how directional antennas improve the localization accuracy of a radio tomographic imaging system based in WSN nodes. Varshney et al. [27] propose a high-throughput bulk transfer protocol that leverages ESD antennas, where data is transmitted over disjoint paths.

3 Design

In this section we describe the optimization of the different protocols in the network stack to support directional communications and improve network performance. We work with the default network stack of the Contiki Operating System [6] based on the IEEE 802.15.4 standard (UDP, IPv6, RPL, 6LoWPAN, ContikiMAC) and make necessary modifications to fully support directional communication.

3.1 Neighbor Discovery

Neighbor Discovery is quite a simple mechanism when we use omnidirectional antennas, as a packet can reach every active radio in the transmission range. Nodes with K-sectored ESD antennas can reach different neighbors using different directions for transmission and reception. For each pair of nodes, there are K^2 sector pairs between the transmitter and the receiver that can result in different link qualities.

In order to implement directional communication, we use a neighbor discovery mechanism that takes into account different antenna directions. We implement the SAND proto-

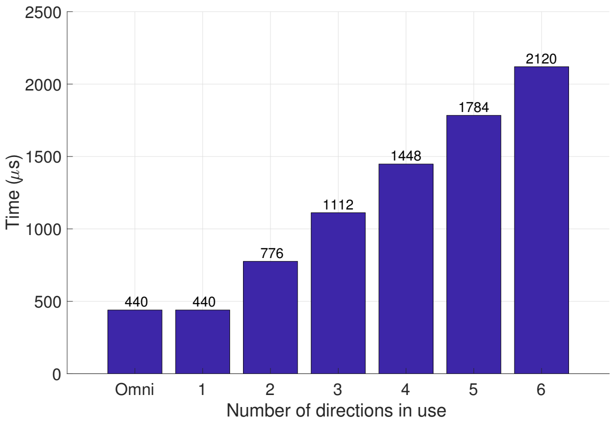


Figure 1. Time required to listen to the channel for the different number of directions in use. This shows how expensive it is to perform multiple CCA checks each time a node wakes up.

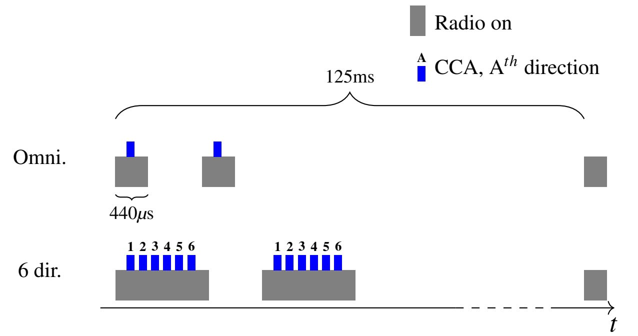


Figure 2. Periodic CCA checks. Comparison between omnidirectional antennas and an ESD antenna with six directions in use.

col [10], where a token passes through the network multiple times, and the token holder sends out probing messages in each direction, with neighbors simultaneously collecting received signal strength (RSS) values for all receiving directions. Through this procedure, a table of RSS values for all the sector pairs is created. The neighbors determine which direction the token-holder should use (by determining which direction yields the highest RSS) for future communication, and pass this information back to the token-holder, which then passes the token on to the next reachable node that has not discovered its neighbors yet.

The tables of RSS values are collected centrally, and used for offline optimizations of directions and routing structure.

3.2 MAC

Radio communication is often the most power consuming activity in WSN, and the energy consumption is dominated by idle listening [25, 2]. The WSN research community has put in significant effort over the past decade to reduce this with different RDC mechanisms [4, 5, 9]. However, the support for directional communication is still missing. The existing RDC mechanisms do not work outright with directional antennas as they simply do not take multiple possible antenna directions into consideration. ContikiMAC [5] is one such RDC mechanism, that keeps the radio off for almost 99% of the time and yet allows seamless communication with other sensor nodes. It is the default RDC mechanism included with Contiki.

We choose to analyze asynchronous RDC mechanisms like ContikiMAC over some new synchronous ones (like TSCH [7]) because in the latter interference is dealt with using time-slotting and channel hopping mechanisms, so using ESD antennas would just increase the transmission range (which would be equivalent to using a higher output power, for example).

In the remainder of this subsection, we review ContikiMAC and introduce DirMAC, a modified MAC layer protocol that uses directional antennas for the transmission and reception of packets.

Packet reception. For packet reception, the ContikiMAC protocol periodically checks the wireless channel for any ongoing transmission by performing Clear Channel Assessment (CCA) checks. These CCA checks are by default performed at a frequency of 8 *Hz*, equivalent to a 125 *ms* period. When working with ESD antennas, the simplest solution is to perform CCA checks omnidirectionally [19, 26] with the main drawback that packets from nodes beyond the omnidirectional range may be lost. If the nodes listen to the channel in one given direction they might observe different channel conditions based on the antenna configuration, being deaf to transmissions in certain direction while being able to receive them in other.

To support directional reception we should perform CCA checks in every possible antenna direction. Figure 1 shows how the listening time increases proportionally with the number of directions in use. Figure 2 shows the periodic channel checks when six directions are in use. In this situation, the overall energy consumption dramatically increases as the radio is kept on for a longer period compared to omnidirectional antennas, and it is known that for convergecast applications the energy consumption of the CCA checks has great impact on the overall energy consumption [25].

The proposed *DirMAC protocol* checks for incoming communications (performing CCA checks) only in the antenna directions that are in use, i.e. directions where neighbor nodes have previously been discovered. This reduces radio-on time. For example, if we have a node with a six-sectored antenna with all the neighbors aligned to one direction, this node will only have to perform CCA checks in that direction, having a radio-on time equivalent to nodes with omnidirectional antennas.

Packet transmission. For the transmission of unicast packets, ContikiMAC uses ideas from the CSMA-CA protocol, where the channel is checked twice before transmitting a packet. If the channel is clear, the node transmits the packet, and if it is busy, it waits for a random back-off time and tries again. In related work CCA checks are performed omnidirectionally [19, 26] with the main drawback that the hidden terminal problem is exacerbated when performing CSMA-CA omnidirectionally, and thus collisions increase.

In the *DirMac protocol*, to support the directional transmission of unicast packets each node sends or forwards each packet to the receiver node using the appropriate antenna direction. The phase information from the neighbors is obtained in the same way as in ContikiMAC, so the only change needed to support directional communication is to select the correct antenna direction before transmitting the packet. Then the channel will be checked in that direction before transmitting, mitigating the hidden terminal problem that Tarter et al. [26] consider a major drawback of using ESD antennas in WSN. When the parent transmits, the receiver node will be listening to the channel and scanning through its sectors and thus it will receive the packet correctly.

For the transmission of broadcast packets, in ContikiMAC each node checks if the channel is clear by using the same procedure as with unicast packets, and then transmits the packet during a whole listening period (called strobe time), to ensure that every node has the possibility to hear it.

The *DirMac protocol* supports the transmission of directional broadcast messages by sending each packet during a whole listening period in every direction in use. This means that for a node with N directions in use, each broadcast packet is going to be transmitted during $N * strobe\_time$ seconds (N times longer than with omnidirectional antennas). Before transmission, the nodes check that the channel is clear in the selected direction.

Both for unicast and broadcast transmissions, multiple directions can serve the same neighbor with different link qualities, so we could optimize the selection of the different directions that the nodes use. The number of directions in use by each node has a great impact on the radio-on time and thus on overall power consumption. There is also a trade-off between network performance and the number of directions in use by the nodes. The more directions we use, the stronger the links are, but power consumption increases.

The relationship between the network performance and antenna directions in use is complex to model, especially as the network size increases. In Section 3.3, we tackle this problem heuristically.

3.3 Antenna Pair Selection

In this section we introduce three different heuristics to optimize the antenna pair selection between neighboring nodes: BestDir, MinDir and OptDir. The objective is to find the mechanism of antenna pair selection that achieves the lowest overall RDC and highest overall PDR in the network.

BestDir Heuristic. The BestDir heuristic determines the choice of the direction to transmit to every neighbor node by choosing the direction which maximizes the signal strength at the receiver. This is a completely distributed method of choosing directions, and no optimization is performed to try to minimize the total number of directions in use.

MinDir Heuristic. MinDir is a centralized heuristic to find the antenna combinations that enable communication between neighboring node while minimizing the number of directions in use by each node. This heuristic cannot be implemented locally as some communication links may only be established when both transmitter and receiver are using some given directions.

In our implementation, computations are performed offline using the RSS tables collected during Neighbor Discovery. The heuristic produces a list of possible links and the directions that each node has to use.

For each node, any neighbor that can only be reached through one combination of antenna directions is designated as a bad neighbor and avoided. Bad neighbors are avoided because they force the heuristic to use a single available combination of antenna directions for communication between the node and the given neighbor, and hence limits the freedom to minimize the total number of directions in use.

Optimization begins by placing all the nodes in the set S_n of non-optimized nodes. The heuristic then iterates through the nodes in the set S_n one-by-one in a random order and evaluates whether there is a single direction in which the node can reach all of its neighbors, except bad neighbors, based on the table of RSS values and given neighbors' directions in use. If such a direction exists, the node is removed from the set S_n. If such a direction does not exist, the heuristic tries again, but allows for bad neighbors to be reachable. If a direction where all neighbors are reachable now exists, the node is removed from the set S_n. Otherwise, the heuristic goes on to check the next node. After it has gone through all the nodes, the heuristic goes through the remaining nodes in S_n one-by-one and evaluates whether there exists combinations of two directions in which the nodes can reach their respective neighbors.

Each time the heuristic has gone through the set S_n, it goes through the set again but allows for one more direction to be used by the nodes.

After following these steps, the set S_n is empty. The combinations of directions in use chosen for all the nodes is saved as a possible solution. All nodes are then put back into the set S_n, and their choice of directions in use kept except for one randomly chosen node where the choice is reset. The heuristic then iterates through the set S_n again in the same manner as before.

When the set S_n is empty again, the new combinations of directions in use are compared to the previous solution. If they are the same, the optimization is complete. Otherwise, the heuristic saves the new solution and repeats the optimization again.

OptDir Heuristic.

In the OptDir heuristic, ideas from MinDir are combined with offline routing optimization that allows us to decrease the number of links in the network. The offline routing optimization yields *a priori* knowledge of the links that have to be established between parents and children. The number of directions in use by every node are minimized only considering these links.

The heuristic is centralized, performed offline and has two outputs: the choice of parent for each node, and which directions to use in each node in order to minimize the total number of directions in use in the network. The choice of node parents is used by RPL as the next hop to the sink, overriding the default metrics.

The heuristic starts by using a metric similar to RPL's hop count. It places all nodes that can reach the sink in Tier 1. All nodes not in Tier 1, but within reach of a Tier 1 node, are placed in Tier 2, and so on until all nodes have been placed in a tier in which they can reach a node in the tier below. The choice of parent is made by selecting the node in the lower tier with the strongest link, i.e. the highest RSS. This Tier-based system minimizes the number of hops to the sink.

After all nodes have chosen their parent, the heuristic uses the same procedure as in MinDir to find the smallest number of directions each node needs to use to reach its parent and all of its children.

4 ESD Antenna Support in COOJA

Existing WSN simulators lack support for ESD antennas such as SPIDA. ESD antennas are also difficult to test in real testbeds as they require time-consuming manual set-up. This difficulty to test ESD antennas in large networks hinders development of WSN protocols that leverage directional communication. By default, the COOJA [21] simulator assumes omnidirectional antenna behavior. We introduce support for the SPIDA antenna in the COOJA simulator for the experiments conducted in this paper. We also describe the antenna model we introduce in the COOJA simulator. Instead of using a fixed antenna range, we modify the COOJA simulator to use the radiation pattern of the SPIDA antenna, calculating the antenna gain based on the angle between the transmitting and receiving nodes.

The total received signal strength (RSS) for a transmission between two nodes A and B is calculated using the log-normal path loss model [13]:

$$RSS = P_{tx} + P_{PL} - 10 \cdot K \cdot \log_{10}\left(\frac{d_{AB}}{d_0}\right) + G_{sp}(\theta_{AB}) + G_{sp}(\theta_{BA}) \quad (1)$$

where P_{tx} is the transmission power, P_{PL} is the path loss at reference distance d_0, K is the path loss exponent, d_{AB} is the distance between nodes A and B, $\theta_{AB} \in [0, 2\pi)$ is the angle between the active antenna direction of nodes A and B and finally $\theta_{BA} \in [0, 2\pi)$ is the angle between the active antenna direction of nodes B and A.

For successful transmissions, the RSS has to be above the receiver sensitivity. For the CC2420 radio, this value is -90 dBm (worst case) [16]. Based on typical outdoor radio environments, the reference distance d_0 is set to two meters, the reference path loss P_{PL} to -52 dBm, and the path loss exponent K to 2.5. Determining transmission success using RSS allows us to implement capture effects in the simulator. A packet can be received correctly despite interference, if its received signal is at least 3 dB stronger than the sum of the received signals from all other nodes, and if the strongest signal arrives within 160 μs of the first waker signal [27, 17]. This time corresponds to the air time of the IEEE 802.15.4 time synchronization header.

To obtain the antenna gain $G_{sp}(\theta_{AB})$ as a function of the angle θ_{AB} between the active antenna direction of the transmitter and receiver nodes, we simulate the SPIDA antenna in the CST Studio Suite® [15] electromagnetic simulator to obtain its radiation pattern. For easy evaluation in COOJA, we approximate $G_{sp}(\theta)$ as a sum of sines of sixth degree, shown in Figure 3, fitted to the CST Studio Suite® data. Figure 3 shows the difference between the radiation pattern of the SPIDA antenna and a reference inverted-F omnidirectional antenna [22]. The SPIDA antenna has 3dB higher gain at 0° increasing the transmission range, and 12dB lower gain at 180°, producing much less interference on neighboring nodes.

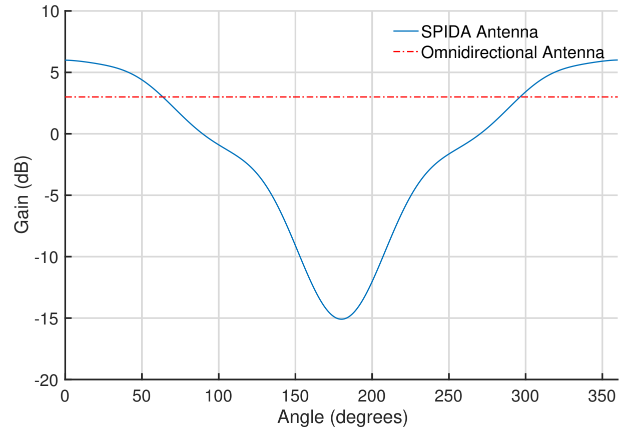


Figure 3. SPIDA antenna gain compared to reference omnidirectional antenna. SPIDA antenna has 3dB higher gain at 0° and thus increases the transmission range, and 12dB lower gain at 180° producing a much lesser interference with neighboring nodes.

Table 1. Values used in the different simulations

	Values
Protocol	Omnidir, BestDir, MinDir, OptDir
Network density	10, 15, 20, 25, 30 nodes/10.000 m^2
Transmission rate	2, 5, 10, 20 pkt/minute

5 Evaluation

We evaluate the performance of the protocols proposed in Section 3 with over 400 simulations. The purpose is to assess the benefits of using directional antennas in a WSN convergecast application, and compare the results with omnidirectional protocols. Therefore, we obtain the average PDR, RDC and energy per received packet (EPRP) of all nodes in the network. We select these magnitudes as representative of the performance of the network protocols.

5.1 Experimental Setup

We evaluate a convergecast scenario, where every node sends packets periodically to the sink node with a fixed rate. The transmission rate determines the application throughput of the network and it is varied according to the values in Table 1. The table also shows the analyzed protocols and the different network densities.

We use the out-of-the-box Contiki implementation of a data collection protocol based on Collect (similar to Collection Tree Protocol [12]) on top of our modified and optimized protocols. The payload of the packets contain e.g. a sequence number, the nodes duty cycles (estimated with the Energest module) and the RPL parent.

We run over 400 simulations in a noise-free environment with networks of 10 to 30 nodes pseudo-randomly distributed over a bounded area. We follow Varshney et al. [27]

by placing the first node ($i = 0$) completely randomly and then placing the subsequent $(i+1)^{\text{th}}$ node at a distance d_i from the i^{th} node, where d_i follows a Gaussian distribution with a mean three quarters of the omnidirectional communication range and a standard deviation of half this range. We work with up to 30 nodes because with larger networks the COOJA simulator takes too much time to complete the simulations.

We enforce a minimum distance between all nodes, as well as a maximum distance to enable communication with omnidirectional antennas. We bound our environment to 100 $\times$ 100 meters to be able to simulate high density networks with a limited number of nodes. Five different network topologies are generated for each network density. Nodes are left running for 4 minutes before starting the collect application, giving the routing protocol time to stabilize. Subsequently, the nodes periodically send data to the sink. We repeat each experiment and vary the transmission rate, using the different rates listed in Table 1.

Each experiment runs for 30 simulated minutes, giving the RDC and PDR time to stabilize. We repeat the simulations for the four protocols listed in Table 1.

The sink is assumed to be connected to a main power supply, i.e. it does not suffer from the same power constraints as other nodes. Therefore, it does not need to keep its radio off to minimize idle listening. This allows it to continuously scan all directions in use for incoming transmissions. However, the continuous scanning diverts CPU time from packet processing, which means the sink does not have time to process incoming packets before they are over-written in the sink's memory by packets received later. Hence, a delay is added, forcing the sink's antenna direction switching period to around 100μs.

5.2 Experimental Results

We evaluate the PDR and energy consumption for convergecast using the experimental setup described in the previous section. Due to the additional energy consumption required to perform CCA checks, it is not evident that our heuristics for directional antennas will reduce the energy consumption compared to convergecast with omnidirectional antennas. We also consider the energy per received packet as it combines both PDR and RDC results. In this kind of applications we want to minimize the energy consumption (and thus the RDC), while maximizing the PDR to collect as much data as possible from the sensors.

Energy Consumption.

In the first set of experiments, we evaluate the potential energy savings possible with directional antennas. As a proxy for energy consumption we use the radio duty cycle (RDC) as other researchers have also done [19].

Figure 5 shows the nodes' average RDC for different transmission rates, where for each point we plot the maximum, minimum and average over the different network topologies. Figure 5a shows that when the traffic is light, both OmniDir and OptDir achieve a duty cycle below 1% which is in line with previous results for RPL [8]. The other heuristics for directional antennas, however, have much higher duty cycles due to the overhead for, e.g., the additional CCA checks. Using directional antennas and the OptDir heuristic, the radio duty cycle remains low, below 2% even when the traffic load is high (Figure 5d) while it drastically increases with omnidirectional antennas.

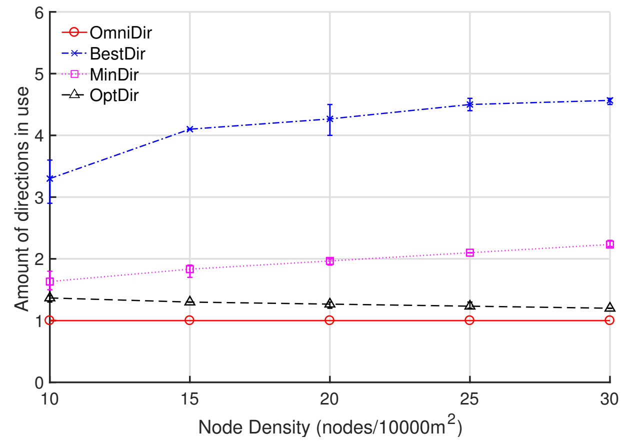


Figure 4. Average number of directions in use by each heuristic, for each network density. OptDir heuristic performs very similar to the omnidirectional reference case, while MinDir and BestDir use more directions in average.

Figure 5a also shows that directional antennas with the BestDir heuristic have a higher energy consumption than using omnidirectional antennas even in high traffic load scenarios. One of the reasons for this high energy consumption is shown in Figure 4. This figure shows that BestDir uses on average much more directions than the other heuristics. Note that for each direction in use, a CCA check needs to be performed. Although the number of hops to the sink decreases in one hop in average when using directional antennas, this is not enough to compensate for the additional CCA checks that force BestDir to keep the radio on for a longer time.

Figures 5a and 5b show scenarios with lower transmission rates and hence lighter traffic. The figures show that using the MinDir heuristic also results in a higher RDC than using omnidirectional antennas. Also in these scenarios, the RDC is dominated by idle listening and thus the reduction in the number of directions in use shown in Figure 4 is not enough to outperform omnidirectional communication. The OptDir heuristic, however, has lower energy consumption than OmniDir. The reason for this is that OptDir uses only slightly more directions than OmniDir. Hence its reception RDC is only slightly higher than OmniDir's. OptDir's transmission RDC, however, is smaller than OmniDir's due to reduced interference from neighboring node achieved with directional antennas. For a network with 30 nodes and a transmission rate of 2 packets per minute, the reception RDC of OptDir is higher than the RDC of OmniDir (0.76% against 0.75%), but its transmission RDC is significantly lower (0.053% against 0.1160%).

Figures 5c and 5d show that as we increase the transmission rate and hence the traffic density, also the MinDir heuristics outperforms OmniDir. As we increase the transmission rate, transmissions dominate the power consumption and since directional antennas decrease the interference from neighboring nodes, the overall RDC of the MinDir heuristic decreases. This effect is exacerbated with the OptDir heuristic, where the decrease of the transmission RDC due to the decreased interference is combined with the decrease of the reception RDC due to the reduction of the number of directions in use.

For a network with 30 nodes and a transmission rate of 20 packets per minute, the RDC of OptDir is 55% lower than in the omnidirectional case (50% lower in reception and 65% lower in transmission). The decrease in the reception RDC can be explained by the effect of overhearing [2], where nodes drain energy by receiving irrelevant packets destined to other nodes. Nodes using directional antennas receive less packets destined to other nodes as the radio energy is concentrated in a single direction. This effect is exacerbated in very dense networks.

Packet Delivery Rate.

The PDR is an important metric for convergecast, as it shows the the percentage of data packets that the sensor nodes can effectively deliver to the sink. Figure 6 shows the average PDR for the different transmission rates. Figures 6a and 6b present the results when the traffic transmissions rates are low and hence the traffic is light. In these scenarios all heuristics perform similar to the omnidirectional case and achieve a PDR of above 99% for transmission rates of two packets per minute and above 98% for transmission rates of five packets per minute.

When the transmission rate increases, as shown in Figures 6c and 6d, all heuristics for directional antennas perform similar and achieve a higher PDR than OmniDir. The reason is the reduction of the interference achieved with the directional antennas. In the most dense scenario with 30 nodes and a transmission rate of 20 packets per minute, OptDir's PDR is 24% higher than OmniDir's.

Energy per received packet.

The energy per received packet (EPRP) combines PDR and RDC and is a good metric to assess the performance of convergecast applications. It is calculated as the total energy consumed by each node, divided by the number of packets received by the sink from that node. Then these values are averaged over every node in the network. Figure 7 shows the EPRP for the different transmission rates. This energy is calculated as the total energy consumed by each node, divided by the number of packets received by the sink.

Figures 7a and 7b show that in scenarios with light traffic, the performance difference between OptDir and OmniDir is low. When traffic is dense, however, the OptDir heuristic consumes up to 46% less energy per received packet than the omnidirectional reference case demonstrating the overall benefit of using directional antennas with full stack optimizations.

6 Discussion

In section 5 we show that we can improve sensor network convergecast performance with directional antennas under certain circumstances. We consider a 6-element antenna for the evaluation as the SPIDA antenna is the reference directional antenna for WSN, also used in most of the related work. If an antenna with more or fewer elements is used, the analysis can be repeated by changing the antenna model in COOJA, but the general ideas of the protocols will still be valid. The main purpose of the protocols is to reduce the energy consumption by minimizing the number of directions in use, while trying to achieve the highest possible PDR, and this can be applied to any sectored antenna.

Another assumption we make is that nodes do not move and that channel conditions are static. Under these circumstances, neighbor discovery and antenna selection heuristics need to be performed once at the beginning, so they have very small impact on the overall energy consumption. If channel conditions are dynamic or the nodes move, we would have to repeat neighbor discovery and antenna selection heuristics periodically, which could have an impact on power consumption and the performance of the network.

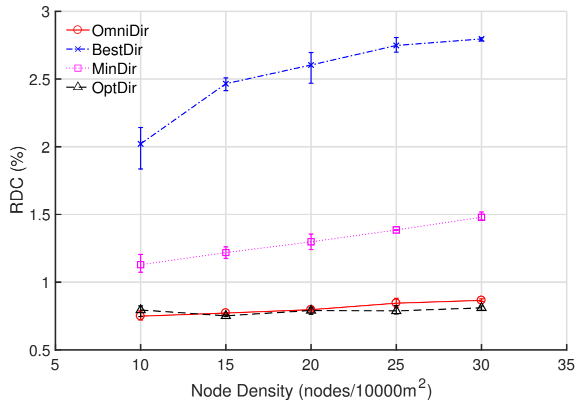
7 Conclusions

The benefits of using directional antennas for convergecast in WSN are not clear in the existing literature. To the best of our knowledge our work is the first to jointly optimize the neighbor discovery, medium access and routing protocols to support directional communication in WSN in a faithful simulation scenario while improving the performance of the network for a convergecast application.

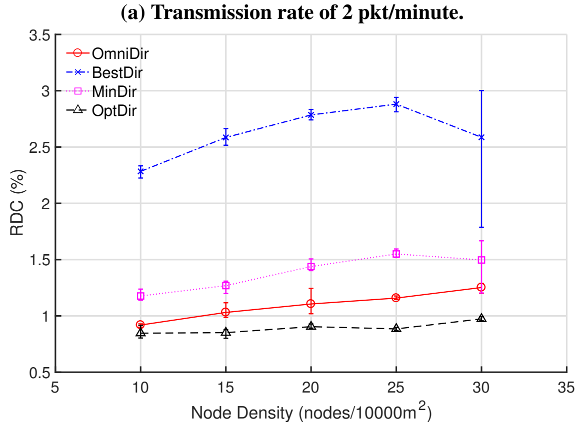
We design and implement DirMAC, a new MAC protocol that fully supports directional communication. We also propose three different heuristics to optimize the performance of the protocols. Our evaluation shows that optimizations at both the MAC and routing layers are needed in order to reap the benefits of using directional antennas for convergecast. The best results are obtained when we minimize the number of antenna directions used by the nodes, and minimize the number of links that each node establishes (OptDir heuristic). We evaluate the performance of these protocols in simulation under different network topologies and different application scenarios. Our results show that the performance of the network can be greatly improved: we obtain the largest performance improvements in networks with dense traffic, where the PDR increases up to 24%, while energy consumption and energy per received packet decrease by up to 55% and 46% respectively.

8 Acknowledgments

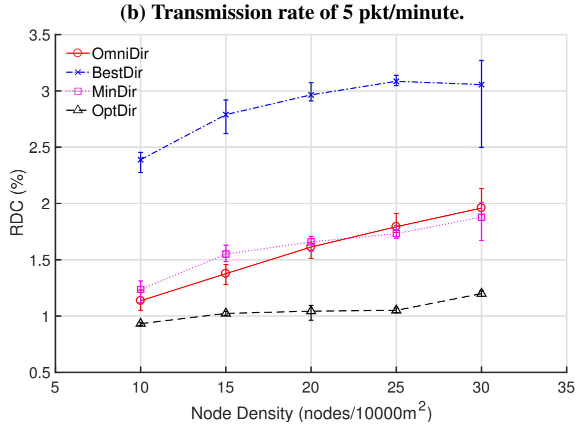
This research was partially supported by ANII, project FMV_1_2014_1_104872. We thank Ambuj Varshney for his contribution to the initial idea and implementation of the protocols, development of the plugin to support the SPIDA antenna in COOJA, and later discussions.



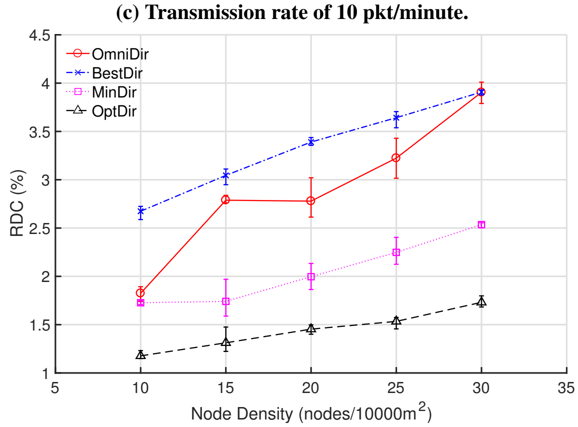
(a) Transmission rate of 2 pkt/minute.



(b) Transmission rate of 5 pkt/minute.

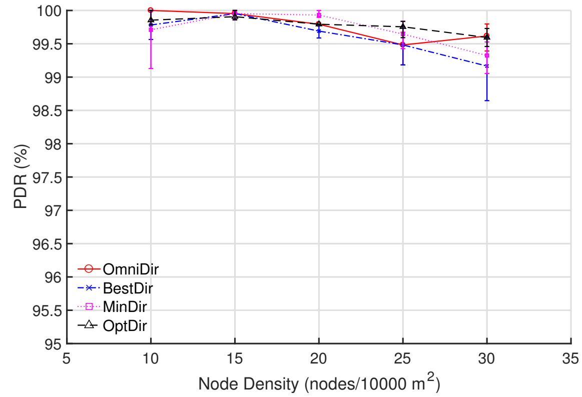


(c) Transmission rate of 10 pkt/minute.

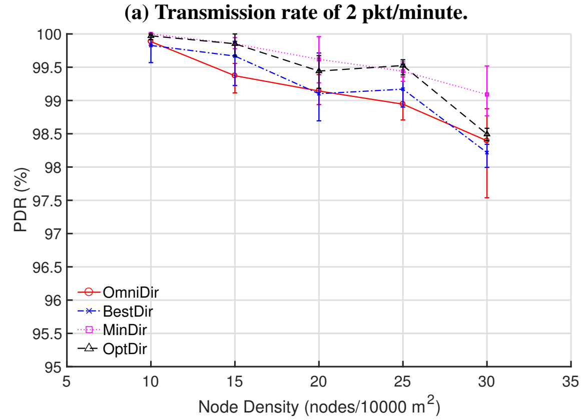


(d) Transmission rate of 20 pkt/minute.

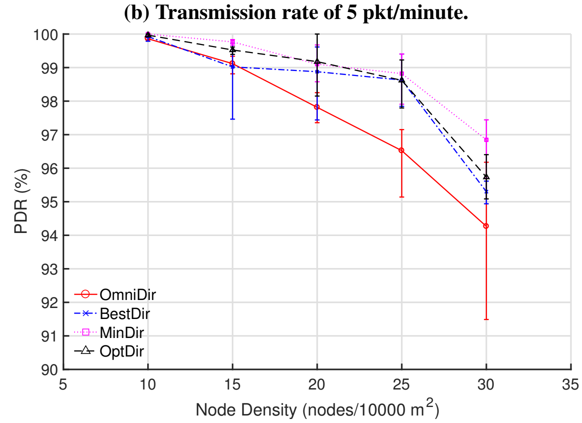
Figure 5. Average radio duty cycles for the different transmission rates.



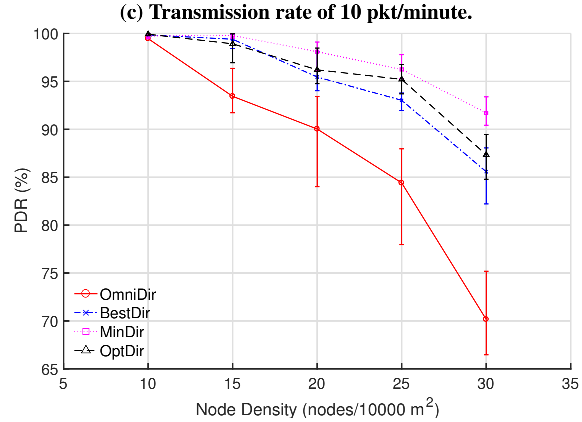
(a) Transmission rate of 2 pkt/minute.



(b) Transmission rate of 5 pkt/minute.

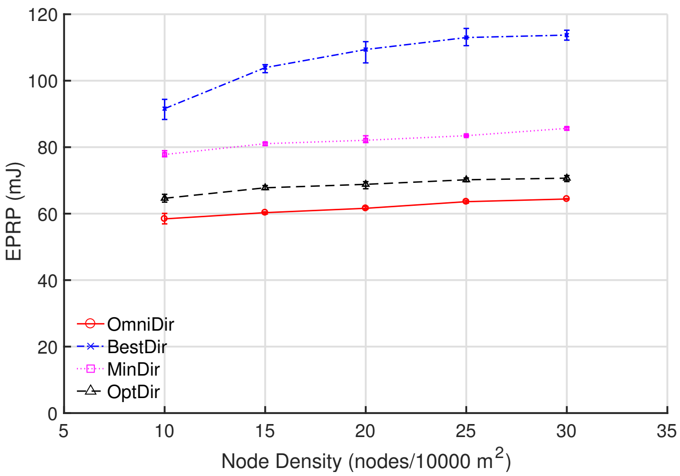


(c) Transmission rate of 10 pkt/minute.

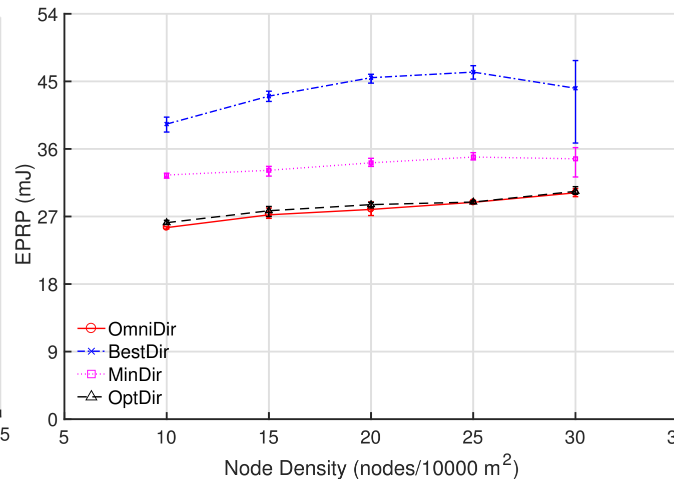


(d) Transmission rate of 20 pkt/minute.

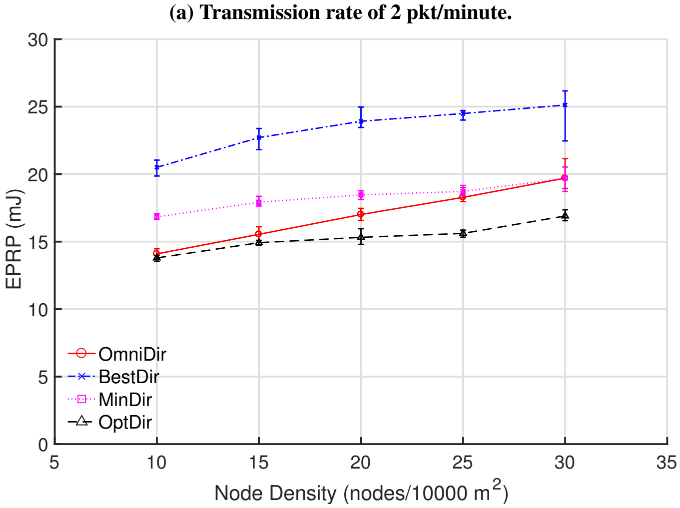
Figure 6. Average packet delivery rates for the different transmission rates.



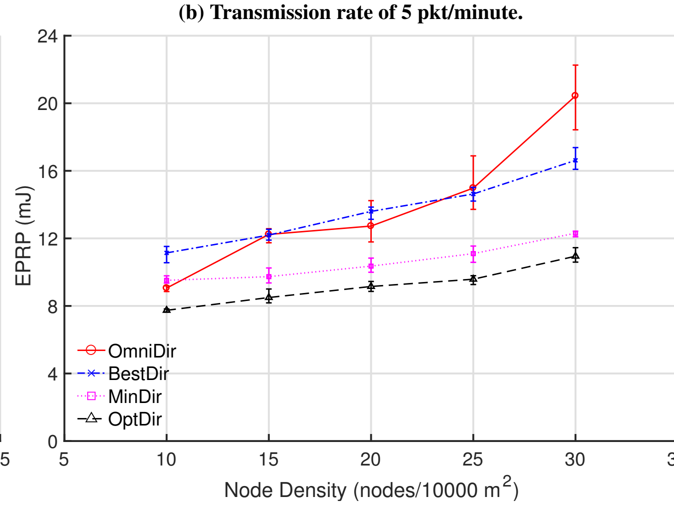
(a) Transmission rate of 2 pkt/minute.



(b) Transmission rate of 5 pkt/minute.



(c) Transmission rate of 10 pkt/minute.



(d) Transmission rate of 20 pkt/minute.

Figure 7. Average energy per received packet for the different transmission rates.

9 References

[1] T. Arampatzis, J. Lygeros, and S. Manesis. A survey of applications of wireless sensors and wireless sensor networks. In *Intelligent Control, 2005. Proceedings of the 2005 IEEE International Symposium on, Mediterrean Conference on Control and Automation*, pages 719–724. IEEE, 2005.

[2] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung. Mac essentials for wireless sensor networks. *IEEE Communications Surveys & Tutorials*, 12(2):222–248, 2010.

[3] A. Boulis. Castalia 3.2, user's manual. *Australia: National ICT Australia Ltd*, 2011.

[4] M. Buettner, G. V. Yee, E. Anderson, and R. Han. X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks. In *SenSys '06: Proceedings of the 4th international conference on Embedded networked sensor systems*, Boulder, Colorado, USA, 2006.

[5] A. Dunkels. The ContikiMAC Radio Duty Cycling Protocol. Technical Report T2011:13, Swedish Institute of Computer Science, Dec. 2011.

[6] A. Dunkels, B. Gronvall, and T. Voigt. Contiki - a lightweight and flexible operating system for tiny networked sensors. In *29th Annual IEEE International Conference on Local Computer Networks*, pages 455–462, Nov 2004.

[7] S. Duquennoy, A. Elsts, A. Nahas, and G. Oikonomou. Tsch and 6tisch for contiki: Challenges, design and evaluation. In *Proceedings of the International Conference on Distributed Computing in Sensor Systems (IEEE DCOSS 2015)*, 2017.

[8] S. Duquennoy, O. Landsiedel, and T. Voigt. Let the Tree Bloom: Scalable Opportunistic Routing with ORPL. In *Proceedings of the International Conference on Embedded Networked Sensor Systems (ACM SenSys 2013)*, Rome, Italy, Nov. 2013.

[9] P. Dutta, S. Dawson-Haggerty, Y. Chen, C.-J. M. Liang, and A. Terzis. A-mac: A versatile and efficient receiver-initiated link layer for low-power wireless. *ACM Trans. Sen. Netw.*, 8(4):30:1–30:29, Sept. 2012.

[10] E. Felemban, R. Murawski, E. Ekici, S. Park, K. Lee, J. Park, and Z. Hameed. Sand: Sectored-antenna neighbor discovery protocol for wireless networks. In *Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks (SECON)*, pages 1–9. IEEE, 2010.

[11] N. Gammarano, J. Schandyy, and L. Steinfeld. DANDi: Dynamic Asynchronous Neighbor Discovery Protocol for Directional Antennas. In *2018 VIII Brazilian Symposium on Computing Systems Engineering (SBESC)*, pages 1–8, Nov 2018.

[12] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss, and P. Levis. Collection tree protocol. In *Proceedings of the 7th ACM conference on embedded networked sensor systems*, pages 1–14. ACM, 2009.

[13] A. Goldsmith. *Wireless Communications*. Cambridge University Press, New York, NY, USA, 2005.

[14] V. C. Gungor and G. P. Hancke. Industrial wireless sensor networks: Challenges, design principles, and technical approaches. *IEEE Transactions on industrial electronics*, 56(10):4258–4265, 2009.

[15] C. S. S. https://www.cst.com, 2017.

[16] T. Instruments. Cc2420 datasheet. *Reference SWRS041B*, 2007.

[17] O. Landsiedel, F. Ferrari, and M. Zimmerling. Chaos: Versatile and efficient all-to-all data sharing and in-network processing at scale. In *Proceedings of the 11th ACM Conference on Embedded Networked Sensor Systems*, page 1. ACM, 2013.

[18] K. Leentvaar and J. Flint. The capture effect in fm receivers. *IEEE Transactions on Communications*, 24(5):531–539, 1976.

[19] L. Mottola, T. Voigt, and G. Picco. Electronically-switched directional antennas for wireless sensor networks: A full-stack evaluation. In *Int. Conf. on Sensor and Ad-Hoc Communication and Networks (SECON)*, New Orleans, USA, June 2013.

[20] M. Nilsson. Spida: A direction-finding antenna for wireless sensor networks. In *Real-World Wireless Sensor Networks*, pages 138–145. Springer, 2010.

[21] F. Österlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt. Cross-level sensor network simulation with COOJA. In *Proceedings of the First IEEE International Workshop on Practical Issues in Building Sensor Network Applications (SenseApp 2006)*, Tampa, Florida, USA, Nov. 2006.

[22] B. Raman, K. Chebrolu, N. Madabhushi, D. Y. Gokhale, P. K. Valiveti, and D. Jain. Implications of link range and (in) stability on sensor network architecture. In *Proceedings of the 1st international workshop on Wireless network testbeds, experimental evaluation & characterization*, pages 65–72. ACM, 2006.

[23] R. Ramanathan. On the performance of ad hoc networks with beamforming antennas. In *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing*, pages 95–105. ACM, 2001.

[24] B. Rodríguez, J. Schandy, J. P. González, L. Steinfeld, and F. Silveira. Fabrication and characterization of a directional spida antenna for wireless sensor networks. In *URUCON, 2017 IEEE*, pages 1–4. IEEE, 2017.

[25] J. Schandy, L. Steinfeld, and F. Silveira. Average power consumption breakdown of wireless sensor network nodes using ipv6 over llns. In *Distributed Computing in Sensor Systems (DCOSS), 2015 International Conference on*, pages 242–247. IEEE, 2015.

[26] G. Tarter, L. Mottola, and G. P. Picco. Directional antennas for convergecast in wireless sensor networks: Are they a good idea? In *Mobile Ad Hoc and Sensor Systems (MASS), 2016 IEEE 13th International Conference on*, pages 172–182. IEEE, 2016.

[27] A. Varshney, L. Mottola, M. Carlsson, and T. Voigt. Directional transmissions and receptions for high-throughput bulk forwarding in wireless sensor networks. In *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*, pages 351–364. ACM, 2015.

[28] A. Varshney, T. Voigt, and L. Mottola. Using directional transmissions and receptions to reduce contention in wireless sensor networks. In *Real-World Wireless Sensor Networks*, pages 205–213. Springer, 2014.

[29] S. Vasudevan, J. Kurose, and D. Towsley. On neighbor discovery in wireless networks with directional antennas. In *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, volume 4, pages 2502–2512. IEEE, 2005.

[30] B. Wei, A. Varshney, N. Patwari, W. Hu, T. Voigt, and C. T. Chou. dRTI: Directional Radio Tomographic Imaging. In *Proceedings of the 14th International Conference on Information Processing in Sensor Networks*, IPSN '15, pages 166–177, New York, NY, USA, 2015. ACM.